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PERIMETER-YARDSTICK TECHNIQUE FOR FRACTURE SURFACE FRACTAL ANALYSIS

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13. ABSTRACT (Maximum 200 words) Local fractal dimensions $\alpha(x,\epsilon)$, which are closely related to "crowding indices" of individual islands and lakes formed by sectioning of fracture surfaces produced in Charpy impact testing of a high-strength and high-toughness steel (ASTM A723) alloy, have been determined by perimeter-yardstick analysis. In this type of analysis, the perimeter of an island or lake on a fracture surface section is measured at several different magnifications, and Richardson's equation is employed to determine fractal dimension of the island or lake. Perimeter-yardstick analysis, which had not previously been applied to fracture surface analysis, yielded $\alpha(x,\epsilon)$ -values ranging from 1.17 to 1.40 (mean: 1.28, standard deviation: 0.08) for Charpy fracture islands and lakes in ASTM A723 steel for ϵ -values near $1.3 \cdot 10^{-4}$ cm. The mean $\alpha(x,\epsilon)$ -value is consistent with the (global) fractal dimension of 1.25 obtained by slit-island analysis of the same fracture surface sections--a value typical of high-strength steel alloys previously studied. The island-to-island and lake-to-lake variations of the local fractal dimensions reflect real variations analogous to differences in the fractal dimensions of the coastlines of Norway and England. Either the fracture surfaces are fractally inhomogeneous or the range of $\alpha(x,\epsilon)$ -values determines limits on the variation of the global multifractal dimensions $D(q)$ and $a(q)$.					
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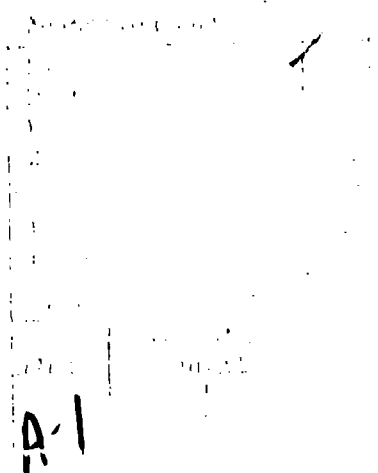
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INTRODUCTION

A major objective in fractal analysis of fracture is to provide quantitative measures of fracture surface complexity and thus to gain deeper understanding of the fracture process. For example, in ductile metals, such as high-toughness steels, the microscopic process that governs the generation of complex fracture surfaces is microvoid formation at grain and carbide interfaces. The microvoids coalesce at the crack tip permitting the crack to advance by internal necking and further flow and rupture of the metal between the voids. Thus, higher toughness in such materials reflects higher resistance to void formation so that a higher stress intensity at the crack tip is required to advance the crack. It is not yet clear how the fractal properties of a fracture surface produced by such a process should depend on material properties.

The fracture surface global fractal dimension (i.e., $D(q)$ for $q=0$) has been observed to vary inversely with the toughness in ductile metals (ref 1). These findings are suggestive, but they are only part of the story. The present work establishes that for high-strength and high-toughness ASTM A723 (modified AISI 4340 with 0.2 at. % V) steel, Charpy impact fracture surfaces exhibit substantial variations in local fractal parameters. The local variations of the fractal parameters imply that the ASTM A723 steel Charpy fracture surfaces are either inhomogeneous and fractal, multifractal, or inhomogeneous and multifractal. The variability of the local scaling should play an important role in a fractal model of the fracture process.

The concept the of "crowding index" was introduced by P. Grassberger, R. Badii and A. Politi (ref 2) to define the local scaling over a range of scales ϵ as $\alpha(x, \epsilon) = \ln(\mu(x, \epsilon)) / \ln(\epsilon)$ where the measure $\mu(x, \epsilon)$ is taken here as the length of coastline in an ϵ -ball centered at x where x is on the set.

We report here on measurements of local fractal dimensions for individual islands and lakes formed by sectioning Charpy impact fracture surfaces of an ASTM A723 steel. We denote the local dimensions as $\alpha(x, \epsilon)$ since they are closely related to "crowding indices." The $\alpha(x, \epsilon)$ values were determined using the perimeter-yardstick technique, which has previously been employed for the analysis of geographical features. Perimeter-yardstick technique is based on Mandelbrot's (ref 3) observation that the length of a coastline increases as the unit of measurement, or "yardstick" is reduced. The length of a fractal coastline $L(E)$ centered at x measured with yardstick E (approximately) obeys Richardson's equation:

$$L(E) = cE^{1-D} = cE^{1-\alpha(x, \epsilon)} \quad (1)$$

where c is a constant and D is the coastline fractal dimension.

The yardstick is the pixel spacing of an image at a given magnification in the present analysis. Thus, the perimeter of an individual island or lake on a fracture surface section is measured at several magnifications and data are fit to Richardson's equation. As demonstrated by log-log plots of perimeter p versus yardstick E , the data are well-represented by Eq. (1), and $\alpha(x, \epsilon)$ -values are determined by least squares fitting of $\ln(p(E))$ versus $\ln(E)$ to Eq. (1). Thus, the measured $\alpha(x, \epsilon)$ -values are average crowding indices for a region near x for the range of scales, $\epsilon \approx E$, over which the island or lake perimeters are measured. That is, $\alpha(x, \epsilon)$ is an average of "crowding indices" for balls of radius ϵ over a region in the neighborhood of x

on the fracture surface defined by an island or lake perimeter. We follow the customary approach and ignore differences of unity (Mandelbrot's rule) in fractal dimensions for a surface and its sections.

The global fractal dimension of the fracture surface sections were also determined by standard slit-island analysis (refs 3-8). The local fractal dimensions $\alpha(x,\epsilon)$ determined by perimeter-yardstick analysis are consistent with the fractal dimension determined by slit-island analysis in the sense that the average $\alpha(x,\epsilon)$ for "randomly selected" islands and lakes is consistent with the global D-value determined by slit-island analysis. The breadth of the distribution of $\alpha(x,\epsilon)$ -values provides additional information about the fracture surface, which can not be obtained via slit-island analysis. If a multifractal interpretation of the data is appropriate, limiting values of the global multifractal dimensions $D(q)$ satisfy

$$D(-\infty) \geq \max_x \alpha(x,\epsilon) \text{ and } D(\infty) \leq \min_x \alpha(x,\epsilon)$$

EXPERIMENTAL DETAILS

The Charpy impact test is a commonly used measure of material toughness. A square V-notched bar is struck and fractured by a swinging arm and the energy absorbed is determined from the amplitude of the swing of the arm. The Charpy specimens were standard 10-mm square V-notched bars, prepared from a sample of ASTM A723 (modified AISI 4340 with 0.2 at. % V) steel, which had been heat treated to produce tempered martensite having nominal strength of 160 Ksi and hardness of 38 on the Rockwell C scale.

Fracture surfaces were: (1) coated with electroless nickel (chosen for hardness and uniformity); (2) polished on a metallurgical grinding wheel; and (3) etched with a 2% nitol solution that attacked the exposed steel. Subsequent light microscopic examination easily distinguished islands and lakes: lakes (polished zones) appeared bright and islands (etched zones) appeared dark in the microscope field. A typical coated and sectioned Charpy specimen showing islands is displayed in Figure 1.

Images of fracture surfaces were digitized via a video camera mounted on the microscope, using the JAVA image analysis system (ref 9). The JAVA system employs a 640 by 480 array of gray levels (light intensity levels) ranging from 0 to 255 in value (0 black; 255 white), with each value representing the darkness of the image at that particular pixel coordinate. Thus, sectioned fracture surface islands and lakes were displayed on the computer screen in shades of gray and stored as arrays of gray levels.

Perimeter measurements for individual islands and lakes were taken at magnifications of 3.2, 5, 10, 20, and 50x. The yardstick values were taken to be the inverse of the number of pixels required to represent 1 mm at each magnification. Islands and lakes were randomly selected from those whose dimensions were suitable for acquisition at magnifications ranging from 3.2 to 50x.

Conventional slit-island analysis was performed on sections of the same Charpy fracture surface. Curve fitting and computation was performed using MATLAB software (ref 10).

RESULTS

Typical perimeter-yardstick results are presented in Figure 2. The $\ln(p)$ versus $\ln(E)$ values are well-represented by straight lines. The lack of (substantial) scatter or curvature in the $\ln(p(E))$ versus $\ln(E)$ curves suggests that the $\alpha(x, \epsilon)$ -values are essentially constant over the perimeters. The deduced local fractal dimensions $\alpha(x, \epsilon)$ are summarized in Table 1. $\alpha(x, \epsilon)$ -values for $\epsilon \approx 1.3 \times 10^{-4}$ cm ranged from 1.17 to 1.40 (mean: 1.28, standard deviation: 0.08) for the "randomly selected" Charpy fracture islands and lakes.

Table 1. Summary of Results

Perimeter-yardstick local fractal dimensions (locally averaged crowding indices) from analysis of islands and lakes formed on sections at magnifications of 3.2, 5, 10, 20, and 50x on Charpy impact fracture surface of ASTM A723 steel.

Lake Dimensions	1.23, 1.39, 1.17, 1.21, 1.21	$\rightarrow 1.24 \pm 0.08$
Island Dimensions	1.40, 1.32, 1.36, 1.31, 1.19	$\rightarrow 1.32 \pm 0.07$
Combined Dimensions		$\rightarrow 1.28 \pm 0.08$

Slit-island global fractal dimension based on 30 islands and 30 lakes from the same sections imaged at a magnification of 10x: 1.25.

Slit-island (perimeter-area) results for 60 islands and lakes on the same sections used for perimeter-yardstick analysis are presented in Figure 3, which is typical of results obtained from Charpy fractures in tempered martensite for ASTM A723 steels (ref 8). The $\ln(p)$ versus $\ln(\text{area})$ values are linear over two orders of magnitude (from 0.0001 to 0.01 cm²) in area. Slit-island analysis yields 1.25 for the global fractal dimension, which is consistent with the mean value of the local fractal dimensions of the "randomly selected" subset of islands and lakes. Values of the global fractal dimension for Charpy impact fractures in A723 steels as reported by McAnulty et al. (ref 8) ranged between about 1.20 and 1.30.

The variations in the "randomly selected" island and lake local fractal dimensions $\alpha(x, \epsilon)$ are real and reflect variations in the local geometry. The variations are analogous to the variations in the fractal dimensions of different geographical coastlines. One might conclude that the fracture surface of high-strength and high-toughness ASTM A723 (modified AISI 4340 with 0.2 at. % V) steel is fractally inhomogeneous or homogeneously multifractal with

$$D(-\infty) \geq 1.40, D(0) \approx 1.25, \text{ and } D(\infty) \leq 1.17$$

The single-branch perimeter-area data support the multifractal interpretation.

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Figure 1. Micrograph of a coated and sectioned Charpy fracture surface (20x). Several layers of nickel coating are visible. The gray islands are steel and the black "islands" are voids.

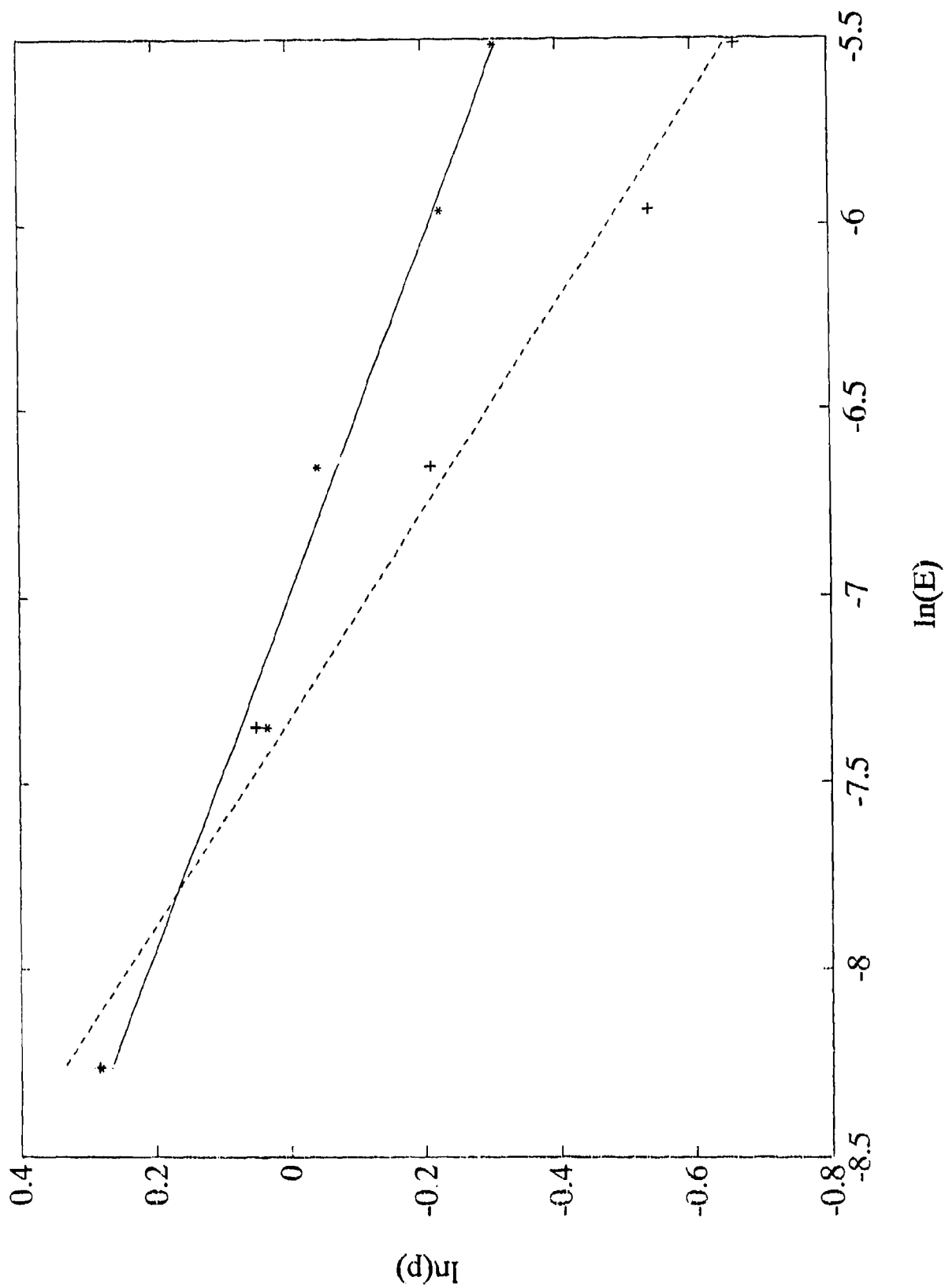


Figure 2 Perimeter-yardstick plots. $\ln(p)$ versus $\ln(E)$ for a typical island and a typical lake. Perimeters were measured at magnifications of 3.2, 5, 10, 20, and 50x. Yardstick values are the inverse of the number of pixels required to represent 0.1 cm at each magnification. The least-squares-fit lines yield averaged crowding index of 1.36 for the island and 1.21 for the lake.

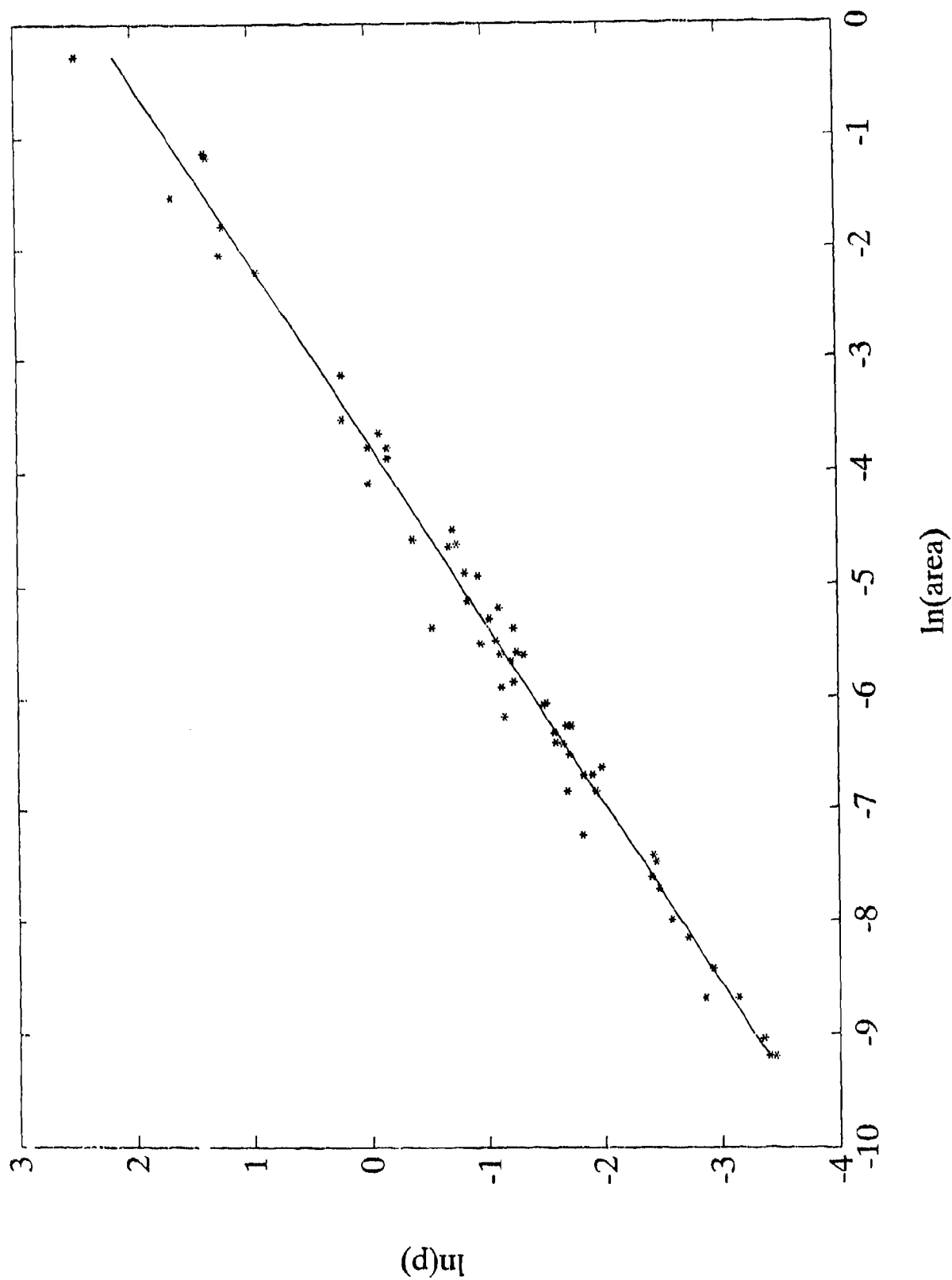


Figure 3. Perimeter-area plot. $\ln(p)$ versus $\ln(\text{area})$ for 60 islands and lakes on the same sections used for perimeter-yardstick analysis. One unit of perimeter is approximately 0.1 cm, and one unit of area is approximately 0.01 cm². The least-squares-fit line yields $D(0) = 1.25$.

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